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# Sensor Placement Methods for Contamination Detection in Water Distribution Networks: a Review

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**Abstract**

Several methodologies have been suggested in the past two decades by different researchers to locate sensors in water distribution networks with different objectives. Even though a large number of methodologies have been developed, there is no consensus amongst researchers on the objectives, methodology and other aspects of sensor placements. The methodologies on sensor placement have been broadly classified into two categories as single objective and multi objective sensor location problems and compared on different basis. A critical review of available methodologies is presented to suggest future research needs for sensor network design for real life networks.



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*Keywords:* Critical Review; Sensor location, Sensor Placement; Water Security; Water Distribution Networks

## 1. Introduction

The main objective of a water distribution network (WDN) is to provide safe water to the consumers in adequate quantity. Water quality may deteriorate substantially during transport from the treatment plant to the consumer. Therefore, water quality at various locations in a public water supply network is routinely monitored. After terrorist attack, more emphasis is being provided to online monitoring of water quality using sensors and several new objectives for location of sensors/monitoring points are being considered.

The new objectives are related to: (i) early detection of any contamination event, such as time to detection (TD); (ii) minimizing the impact or consequences of contamination event, such as volume of water consumed (VC), population exposed to contamination (PE), and extent of contamination (EC). Theoretically, contaminant may enter

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at any point in WDN and at any time, which obviously require monitoring at each node and is practically not feasible. Therefore, attempts have also been made to cover maximum population with limited number of sensors considering (i) associated risk (Risk) and/or (ii) maximizing detection likelihood (DL) of contamination events. A sensor may detect a contamination event falsely or may not detect a contamination event if the contamination concentration is below certain detectable limits. Further, there may be delay in response from sensors deployed. Therefore, additional objectives as minimization of sensor response time (SRT), minimization of number of failed detection (NFD)/minimization of probability of failed detection (PFD) and sensor detection redundancy (SDR) have also been considered. Time delay is used to differentiate two systems of MSs having same DL but different TD.

The main objective of this paper is to review the methodologies related to locations of monitoring points or sensors in WDNs. Several methodologies have been developed to tackle the problem of sensor placements with single or multiple objectives. Hart and Murray [1] comprehensively reviewed available literature till 2008-09 on sensor placement strategies and identified key issues that need to be addressed in future work. A lot of research work has been reported after that. A comprehensive review until date is provided in this paper along with critiques. Further, some of the issues that are required to be considered in future work are presented.

## 2. Single and Multi-objective Sensor Location Problems

Based on number of performance objectives, research work on location of sensors/monitoring stations is classified herewith as single objective or multi-objective problems. Performance objectives are those which provide performance characteristics of monitoring system. General parameters considered for comparison of different methodologies are: (i) need of hydraulic and water quality simulation; (ii) methodology used for solving problem; (iii) Network(s) considered for illustration; and (iv) fixed/ variable number of sensors. All the works based on any single objective are presented in Table 1 [2-22].

### *2.1. Single Objective problems*

Safe quality of water at monitoring node assures delivery of safe water at all upstream nodes through which major portion of supply (termed as coverage criteria) received at monitoring node has passed. The DC of MS is defined as total demand of all those nodes, which can be assumed to be safe if quality of water at monitoring node is safe [2]. Lee and Deninger [2], Alzahrani et al. [5], and Afshar and Marino [9] used MIP, GA and ACO respectively to locate given number of MSs to maximize the DC based on selected coverage criteria. Woo [4] emphasized use of water quality simulation to develop coverage matrix. Kumar et al. [3] and Kansal et al. [7] proposed more systematic way of preparing coverage matrix and suggested heuristic method to locate MSs one by one, by selecting best location first and modifying coverage matrix by eliminating nodes already covered to select next station. Ghimire et al. [6], and Rathi and Gupta [8] also suggested heuristic methods to simplify the problem. Method based on DC gives importance to coverage and therefore tries to locate MS as far away as possible from source based on coverage criteria. They aregood for location of MS required for regular monitoring against accidental contamination.

Anearly detection of contamination event is desirable. Kumar et al. [10] suggested TD, defined as the time elapsed between the entry of contaminant and its detection by any of the MS and used it as a measure for level of service (LOS) to consumers. They identified best monitoring locations one by one by constructing and using travel-time matrix for desired LOS.Chastain et al. [12] developed a heuristic methodology considering extended period water quality analysis for creating database of water system responses by injecting contaminant at each node. The method searched the best locations of MS one by one to maximize the covered nodes with the condition of time to detect. Rathi and Gupta [13] also suggested a heuristic method, which works on appended shortest travel time tree to identify best locations of MSs to achieve desired T-hr LOS. The number of MSs increases as the desired LOS increases. With constraints on number of sensors, the desired LOS may not be achieved. Most of the multi objective sensor location methodologies considered TD as one of the objective.

Table 1. Single objective based sensor location methodologies.

| Objective | Citation | Hydraulic/ Water Quality Simulation | Methodology Used / Optimization Solver | Network as Case study/ Illustration | Fixed /Variable number of sensors | Remarks |
|---|---|---|---|---|---|---|
| DC | Lee et al. [2] | SHS | IP | Hypothetical two loop network[1], Network of Flint,Michigan[2]& Cheshire,Connecticut[3] | Fixed | |
| | Kumar et al. [3] | SHS | Heuristic | Hypothetical network with two source nodes[4] | Variable | |
| | Woo et al.[4] | DH &WQS | IP | Small Hypothetical network[5] | Fixed | |
| | Al-Zahrani et al. [5] | SHS | GA | A hypothetical WDN with three source nodes[6] | Fixed | Regular or Routine Monitoring |
| | Ghimire et al. [6] | Not required | Heuristic | BWSN Net 1[7]& Net 2[8] | Variable | |
| | Kansal et al. [7] | SHS | Heuristic | Manendragarh Town Network[9], India. | Variable | |
| | Rathi et al. [8] | SHS | Heuristic | Networks[1,9,4],Network of part of Nagpur city,India[10] | Variable | |
| | Afshar et al. [9] | SHS | ACO | Network of City of Babol, Iran[11] | Variable | |
| TD | Kumar et al. [10] | DHS | Heuristic | Any town[12], USA | Variable | |
| | Kansal et al. [11] | SHS | Heuristic | Network[9] | Variable | Accidental |
| | Chastain [12] | DH & WQS | Heuristic | Network[12] | Variable | Accidental/ Intentional |
| | Rathi et al. [13] | SHS | Heuristic | Networks[4, 9,10] | Variable | Accidental |
| | Cozzolino et al. [14] | DH & WQS | Heuristic | Network[13] | Variable | Demand Uncertainty |
| VC | Kessler et al. [15] | DHS | Heuristic | EPANET Ex.1[14] and Network[12] | Variable | Accidental |
| | Ostfeld et al. [16] | DH & WQS | GA | Networks[14, 12] | Fixed | Intentional |
| | Ostfeld et al. [17,18] | DH & WQS | GA | EPANET Ex.3[15] (2005) Network[14,12] (2005b) | Fixed | Intentional |
| PE | Berry et al.[19] | SHS | MIP | Network[15],EPANET 2.0 Ex.2[16],Network of 470 nodes & 621 pipes[17] | Fixed | Intentional |
| | Shastri et al. [20] | DHS | L-shaped BONUS algorithm | EPANET 1.0 Ex.2[18], EPANET Ex 1[19], Network[18] | Variable | Demand Uncertainty |
| | Rico-Romizoz et al. [21] | DHS | Stochastic decomposition | Network[18] | Fixed | Uncertainty in AR and PD |
| | Uber et al. [22] | DH & WQS | Heuristics | Network[20] | Fixed | Intentional |

Notations: SHS-Steady hydraulic simulation. DH & WQS - Dynamic hydraulic and water quality simulation, AR- Attack Risk, PD- Population Density. Superscript used with networks indicates networks considered by different researchers. These are same if their numbers are same.

Kessler et al. [15] suggested total volume of contaminated water consumed (VC) before detection of any event to quantify the impact of contamination event. The LOS is decided by pre-specified value of VC. They developed pollution matrix for a given level of service and identified an appropriate set of MSs, which covered all events. Ostfeld and Salomons [16] considered random multiple contamination events to decide location of MSs. Random pollution matrix was generated by considering LOS in terms of VC and GA was used to identify location of MSs.

Ostfeld and Salomons [17,18] extended the methodology to consider randomness of flow rate of injected pollutant, randomness in consumers' demands, and the detection sensitivity and response time of MSs.

Berry et al. [19] considered LOS in terms of expected fraction of population at risk and identified optimal sensors locations using MIP. Berry et al. [23] and Propato et al. [24] formulated MIP model in such a way that wide range of design objectives can be accommodated in the formulation, either individually or jointly. Berry et al. [23] quantified the impact of each contamination event by multiplying: (1) The probability of events, (2) A binary (1, 0) contamination indicator and (3) impact value evaluated from dynamic water quality simulation. Propato et al. [24] considered minimization of impact associated with contamination scenario in terms of TD, PE, VC, contaminated mass consumed (CMC), and probability/percentage of failed detection (PFD). Since projected nodal demand has inherent uncertainty, several researchers incorporated it in deciding sensor locations with objective of minimizing expected population exposed [20,21] or detection time [14].

Each objective has its own advantage and provides different set of locations. Watson et al. [25] demonstrated that sensor placement using one objective provides greater risk. They observed that majority of objectives are uncorrelated, and an optimal solutions associated with one objective function could be highly sub-optimal with respect to another design objective. Murray et al. [26] compared sensor placement solution considering three objectives PE, EC, DL using 8 example networks of varying size for illustrations and showed that number of sensors needed for various objectives depends upon marginal benefit achieved or acceptable risk defined by water utilities.

Bahadur et al. [27] assessed the impact of both spatial and temporal population variability on sensor network design and observed it to be significant. Since limited sensors are to be used, this makes sensor location crucial. Therefore, in order to provide a balance solution using limited number of sensors researchers suggested different algorithms based on multiple objectives.

### *2.2. Multi-objective problems*

Various researchers had used two types of multi objective approaches. Some researchers considered the approaches in which the objective functions remain mutually distinct and result is expressed in the form of Pareto front ([24],[28-36]) and other approaches in which the different objectives considered are grouped together in a single objective function which is then solved using optimization solver[37-42]. The available multi-objective methodologies are given in Table 2 in the chronological order of their development.

It can be observed from Table 2 that few additional objectives such as contamination source detection likelihood (CSDL) as used by [31], Risk as used by [33], Detection Likelihood (DL) and Response delay of Sensors as used by [17,18], Sensor Detection Redundancy (SDR) as used by [31,32]etc. are suggested as performance indicator of monitoring system. Since limited number of sensors is provided for monitoring, there is possibility that some of the contamination events are not detected by any of the sensor. Therefore, detection likelihood, defined as probability of contamination events being detected by any sensor, or probability of failed detection, defined as probability of contamination events not being detected by any of the sensor are considered.

Further, it may be possible that contamination events are detected by multiple sensors, and therefore term sensor detection redundancy defined as probability of detection of contamination event by specified number of sensors within specified time. The response delay by sensor is measured by time elapsed between registration of contamination event at sensor and response provided by it [17, 18];[48]). Bristow et al. [49] model the response time in various phases and defined it as the time between initial detection of a contamination event and individual user stops using contaminated water.

As mentioned earlier TD is the most preferred objective in multi-objective problems as it forces early detection of contamination events. It is coupled with one or more complementary objectives that quantify impact of contamination event with one or more competing objectives such as detection likelihood or coverage. Ostfeld et al. [50] compared solution provided by several algorithms based on four objectives: (1) TD; (2) PE; (3) VC; and (4) DL. The solutions provided by different algorithms were quite varied.

Table 2. Multi- objective sensor location methodologies.

| Objective | Citation | Hydraulic/ Water Quality Simulation | Methodology Used / Optimization Solver | Network as Case study/ Illustration | Fixed /Variable number of sensors | Remarks |
|---|---|---|---|---|---|---|
| PE, EC | Carr et al. [43] | SHS | Branch and Bound | Application not shown | Fixed | Uncertainty in AR and PD |
| TD, VC, PE, EC and PFD | Propato [24] | DH & WQS | MIP and Heuristic | Networks[18]& case study[19] | Fixed | |
| | Berry et al. [23] | DH & WQS | Branch and bound | SNL-(1[20],2[21],3[22]) | Fixed | |
| PE, MC | Berry et al. [44] | DH & WQS | IP, Local Search & NLP | Networks[20, 21,22] | Fixed | Imperfect sensors |
| TD,PE,VC, DL | Dorini et al. [28] | DH & WQS | Modified cross-Entropy algorithm | Networks[7,8] | Fixed | Reduced Network[7] |
| TD, PE, VC, DL | Propato et al. [37] | DH & WQS | MIP | Networks[7] | Fixed | |
| TD, VC, DL | Wu et al. [38] | DH & WQS | GA | Networks[7,8] | Fixed | Reduced Network[7] |
| TD,PE, DL | Huang et al. [30] | DH & WQS | GA | Networks[7,8]& Case study[23] | Fixed | Reduced Network[23] |
| DC, TD, VC, PE, DL | Eliades et al. [29] | DH & WQS | Heuristic | Networks[7,8] | Variable | |
| TD, DL, SDR, CSDL | Preis et al.[31] | DH & WQS | NSGA-II | Networks[7,8] | Fixed | |
| TD, DL, SDR | Preis et al.[32] | DH & WQS | NSGA-II | Networks[15] & Richmond WS[24] | Fixed | Heuristic method for CES |
| | Austin et. al [34] | DH & WQS | NSGA-II | Networks[15] | Fixed | Imperfect mixing at nodes |
| | Aral et al. [41] | DH & WQS | PGA | Networks[7,8] | Fixed & Variable | |
| TD, PE | Krause [39] | DH & WQS | Greedy and SA | Networks[7,8], Large network(21000nodes)[25] | Fixed | |
| | Comboul M et al. [45] | DH & WQS | Greedy algorithm | Networks[26] | Fixed | Nodal demand uncertainity |
| VC, PFD | Guidorzi et al. [35] | DH & WQS | NSGA-II | City of Ferrara[27] | Fixed | Valves & hydrants operation to reduce VC |
| Risk in terms of VC&NFD | Weickgenannt [33] | DH & WQS | NSGA-II | Almelo[28](The Netherland) | Variable | Heuristic (IBSM) method for CES |
| DL, PE | Dorini [40] | DH & WQS | Heuristic method | Networks[7,8] | Fixed | Algorithm SLOT |
| DL, PE | Xu [42] | DH & WQS | Heuristic | Networks[7] | Fixed | Robust Model for accidental contamination |
| Time delay, SDR | Shen et al. [36] | DH & WQS | NSGA-II | City of Guelph[29] | Variable | Select specific incident list event |

| | | | | | | |
|---|---|---|---|---|---|---|
| TD,VC,PE, MC | Cozzolino et al. [46] | DH & WQS | GA | Networks[13] | Fixed | |
| DL, CSDL | Xu et al. [47] | DH & WQS | MIP Solver | Networks[7] | Fixed | Imperfect Sensors |

Notations: SHS-Steady hydraulic simulation. DH & WQS- Dynamic hydraulic and water quality simulation, AR- Attack Risk, PD- Population Density, CES- Contamination event sampling, IBSM- Importance based sampling method, SLOT- Sensor local optimal transformation system. Superscript used with networks indicates networks considered by different researchers. These are same if their numbers are same.

Even though various research groups have demonstrated the ability to solve large-scale problems, this is not a robust capability that can be applied by potential end users. This raises important questions about the reliability of such designs, and it highlights the need of memory-limited optimizers. GA is the most preferred solver for multi-objective optimization problem. The computational requirement in GA increases with the size of network and number of contamination scenario required to be considered, which poses restriction on its application to large network problems. Heuristic algorithms have their own limitations. Another problem observed especially in developing country that no well-calibrated model for the network is available which is considered to be the most important requirement of most of methodologies. Therefore, recently researchers have developed the methodologies for real world problem to tackle the complexity of the network and reduce the computer runtime [54-58].

It can be observed from the reported literature that there is no consensus amongst researchers on number and type of performance objectives to be considered and several other issues related to sensor location problem. Considering the applicability of algorithms developed in future to real life networks some issues are raised in next section, which may be helpful in developing some consensus amongst researchers.

## 3. Issues need consensus for future research

- Original or Reduced Network: A real life network may involve thousands of pipe and nodes, and numbers of sensors are restricted. Considering each and every node of original network as possible location of sensor may unnecessarily increase computational burden, which can be significantly reduced by suitably eliminating some of the nodes from list of candidate nodes such that sensor placement accuracy is not affected
- Number of loadings: Water demand changes throughout the day so as the water level changes in the reservoir throughout the day, and therefore practically flow scenario in network changesin every moment. This requires consideration of dynamic analysis at suitable interval. The computational requirement can be substantially reduced by identifying few important scenarios with respect to nodal demands, pumps on and off situation and flows in and out conditions from tanks.
- Number of contamination events and their locations: A contaminant may enter in network from any point and at any time. Further, there could be more than one location of contaminant intrusion at any time. Instead of considering every node as possible location of entry of contaminant, few vulnerable locations can be selected to reduce the computational work.
- Number of performance objectives: One objective is certainly not enough and multiple objectives are necessary to obtain a balanced solution. Selection of too many objectives at a time increases the computational requirement. Selection of objectives should be such that a balanced design could be obtained with respect to different objectives. Some complementary type of objectives can be dropped.
- Type of solution methodology: Preferred solution methodology is one that can prioritize selection with respect to different objectives considered in the sensor location problems. Prioritize selection helps in future extension of monitoring locations.

## 4. Summary and conclusions

The issue of water system security after the terrorist attack in 2001 has motivated several researchers to develop a methodology for sensor location to prevent public from impact of deliberate contaminations. Several performance objectives for evaluating monitoring system have been considered. In spite of lot of research there is no consensus amongst researchers on several issues related to sensor location problems. A critical review of available methodologies is presented in this paper with a view to raise issues requiring consensus amongst researchers. The research work pertaining to these issues are highlighted for developing consensus amongst researchers for future research work on sensor location problems.

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